ISBN 978-0-620-44584-9
Proceedings of the 16th International Symposium on High Voltage Engineering

INCLINED PLANE TEST, INFLUENCE OF TRANSFORMER POWER

K. L. Chrzan
Wroclaw University of Technology, Institute I – 7, 50-370 Wroclaw, Poland
Email: krystian.chrzan@pwr.wroc.pl

Abstract: The inclined plane method is one of a few other tests that prove the material resistance to erosion and tracking caused by surface discharges. In this paper the review of inclined plane tests and the influence of additional factors were shown. A simple method for evaluating the voltage source rigidity was proposed.

1. INTRODUCTION

The wide application of polymer materials as high voltage insulation begun after introduction of epoxy resins in 1950s. At the beginning the polymers were used for indoor conditions. The attempts with outdoor epoxy insulators undertook in 1960s were not successful. Rosenthal company introduced composite insulators made of silicone in 1976. Since this year the number of new insulators increased slowly first, but after 1990 quicker and quicker. To most important advantages of composite insulators belong: elasticity, light weight, resistance to mechanical impulses (vandalism) and the better forming possibility. The profile of polymer insulators can be complicated and their parts can be thinner than that made of ceramics. Unfortunately, the polymers are many times less resistant to surface discharges than ceramic materials. Therefore a few methods was worked out to check the polymer materials properties under the influence of electrical stress, moisture and contamination. This paper describes one of them, the inclined plane method.

2. POLYMER PROPERTIES

The most important polymer properties in respect to outdoor high voltage application are [1]: resistance to tracking and erosion, resistance to corona and ozone, resistance to chemical and physical degradation by water, tear strength, volume resistivity, breakdown field strength, resistance to chemical attack, resistance to weathering and UV, flammability, arc resistance, glass transition temperature, hydrophobicity.

3. RESISTANCE TO SURFACE DISCHARGES

Polymer materials are organic materials that consist of molecules that are not tightly bonded to each other as in the inorganic materials, porcelain and glass. Hence, they can be degraded at much lower temperature than ceramic materials. Most polymer materials contain carbon atoms. Upon degradation, carbon makes the surface conducting and leads to electrical failure as the insulator is no longer able to withstand the applied voltage. The formation of carbon conducting path on the surface is referred to as tracking [2]. If the carbon can be removed from the surface either by physical or chemical means, then there is no tracking. Removal of material leaves behind an eroded path. If material erosion is significant then it could potentially lead to insulator failure by exposing the less resistant materials e.g. the fiber glass rod to the outdoor conditions. Usually erosion is a much slower process of degradation than tracking.

The tracking and erosion resistance is dependent on the chemical composition of polymers. In some materials, such polyester, bisphenol epoxy or polyethylene free carbon is formed upon degradation. In other polymers such as silicone rubber, carbon is removed as gaseous CO_2 by-products, i.e., some materials will erode rather than track. The highest degradation resistance show silicones, then EPR rubber, cycloaliphatic epoxy, polycarbonates belong to least resistant materials.

By the addition of suitable inorganic fillers to the base material, tracking can be eliminated and the resistance to erosion can be increased. The most common type of inorganic fillers are alumina trihydrate (ATH) and quartz (SiO_2). Hydrated fillers are superior to unhydrated fillers in terms of their effectiveness in improving the tracking and erosion resistance. The silicone rubber containing 50% ATH have about 2,5 times higher erosion resistance than unfilled silicone rubber. The addition of inorganic fillers improves certain properties of material, but several other properties may be degraded. With increased filler concentration the elongation and hydrophobic properties are reduced but tensile strength is improved.

There are a few methods for evaluation of tracking and erosion resistance, to the most important belong:

resistance to high voltage, low current arc, (dry arc resistance), this method was established as ASTM standard in 1948 [3, 4],

method for the determination of the comparative tracking indices CTI (droplet method), the first method of this type was Admiralty test [3, 5],

Merry-Go-Round method, Rotating Wheel Deep test, worked out by Ontario Hydro in 1960s [7, 8],

Long-term salt fog test, the first salt fog test was established in General Electric Company in 1956 [3, 9].

ISBN 978-0-620-44584-9

For materials applied under outdoor conditions the resistance to chemical and physical degradation by water is also a key property. The procedure given in the high voltage diffusion-breakdown test enclosed in IEC 61462 and IEC 61109 standards describes how to measure the breakdown voltage of samples after the boiling water bath.

4. INCLINED PLANE TEST IPT

Inclined plane test [10] was proposed by Mathes and Gowan in 1961 [11] and worked out as the ASTM D2303standard in 1964. On sample with the dimension of 120 × 50 × 6 mm two pair of electrodes are fixed 50 mm apart. Eight layers of filter-paper are clamped between the top high voltage electrode and the specimen to act as a reservoir for the liquid contaminant. The 0,1 % solution of ammonium chloride (NH_4Cl) with the conductivity of 2,53 mS/cm is fed by a small pipe to the to electrode. The ammonium chloride when evaporated in high temperature does not leave the residuals and therefore is also used in CTI test. The electrolyte flow is precisely regulated and it depends on the value of test voltage. The peristaltic pump and special flow meters allow the high accuracy of contaminant application rate. A small amount of non-ionic wetting agent is added to the electrolyte, e.g. isooctylphenoxy-polyethoxyethanol TRITON-X100 is able to wet even so hydrophobic material as silicone rubber. The sample is fixed at the angle of 45° and the contamination liquid flows through the lower surface of the test sample (Figure 1). The method consists of two alternative test procedures: the constant value of the test voltage is used for 6 hours (procedure 1) or the voltage is increased after one hour (procedure 2). The sample passes the test when the erosion channel or tracking path is shorter than 25 mm after 6 hours and the current was smaller than 60 mA. The additional criterion is the material loss measured after drying of the sample and removing of degradation products.

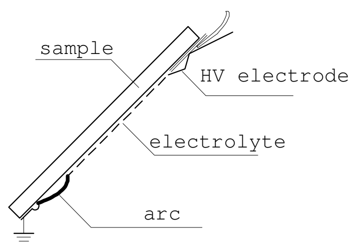

Figure 1: Illustration of the inclined plane test

When the voltage is switched on, the dry band is formed and electrical discharges appear at the bottom electrode. This localized and persistent discharge activity can rise the temperature to cause degradation. The temperature rise due to surface activity depends on the magnitude of leakage current, the thermal characteristics of the material and surroundings, and discharge duration in a particular location. The surface temperature rise of the sample T is given by the expression (1) [12]

$$T = \frac{QR}{K}\left[\frac{2}{\sqrt{\pi}}\left(\frac{\alpha \cdot t}{R^2}\right)^{0,5}\left(1 - e^{-R^2/4\alpha \cdot t}\right) + erfc\frac{R}{2\sqrt{\alpha \cdot t}}\right] \quad (1)$$

Where: Q is the heat flux, R the radius of the discharge, K the thermal conductivity of the material, t the time duration of the discharge in a particular location, the complementary error function erfc (β) = 1-erf (β), and erf (β) the Gaussian error function.

Figure 2 shows the temperature rise for different discharge duration as a function of leakage current. It is clear that the surface temperature high enough for material degradation can be obtained only if the discharge stays at the same location for many cycles without extinguishing.

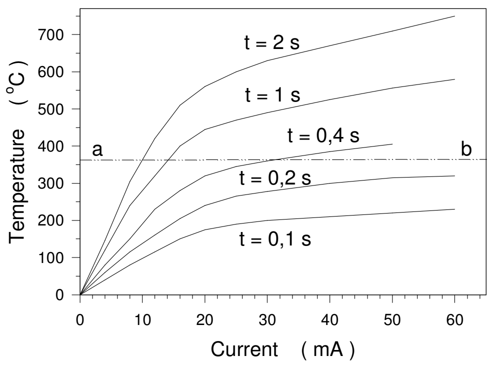

Figure 2: Variation of localized surface temperature with discharge duration in one spot as the parameter [12]. This plot is for silicone rubber with 50% ATH filler, cooling coefficient =0,02 W/cm^2 °C, discharge radius 0,4 cm. a-b line: Material degradation onset temperature determined by thermogravimetric analysis. Courtesy of IEEE and Ravi S. Gorur

During testing according to inclined plane method the sample is exposed to very high electrical stress. The test conditions were specially so hardly selected to damage the polymer material in a relatively short time. The method compares the tracking and erosion resistance of basic polymers and influence of different fillers. There is no direct comparison between the IPT results and field performance of insulators. The outdoor insulators are usually not exposed to so high stress like in IPT. However, there is an opinion that the materials that withstand the IPT under the voltage of 3,5 kV or greater for 6 hours can be used for outdoor applications and the materials that do not withstand the test under the voltage of 2 kV or less can be used only for indoor conditions. The table 1 lists the IPT results for different materials taken from the literature. Some additional parameters like weight loss or test duration were given in the column entitled as “test result”. The result “4,0 kV/0,2 h for polyester resin means that under 4 kV the material damage was found after 12 minutes.

ISBN 978-0-620-44584-9

Table 1: Results of IPT for different materials.

Material	Test result (kV)	Re-marks	Source
Polyvinylchloride PVC	0,75		[13]
Buthyl rubber	1,2		[13]
Polycarbonate	1,0-1,5		[14]
Polyester resin	4,0 kV/0,2 h		[15]
Bisphenol epoxy	2,0		[14]
Cycloaliphatic epoxy	3,5-4,0		[16, 17]
Teflon PTFE	3 kV, 4 mm^3/h		[18]
Polymer concrete	2,5-6,0		[19]
EPDM	< 3,5 4,0/0,8 h	Sample burned	[20] [21]
Ethylene vinyl acetate EVA	4,0	< 50% ATH	[12]
Silicone rubber	3,0 - > 5		[22, 23]

4. MODIFICATIONS OF IPT

The test conditions of IPT are so severe that they usually not occur in the field. Therefore some modifications try to lower the stresses and prolong the test duration. These efforts appear to result from the wide spreading and relatively simple apparatus of this method as compared to the rotating wheel and the long-term salt fog test. The simplest modification is the change of electrolyte type. Liang studied the influence of different electrolytes on the erosion resistance of silicone rubber filled with ATH using the 6 kV for 6 hours. It was shown that the erosion resistance depends on the boiling temperature of the electrolyte (table 2). The smallest erosion is caused by $MgSO_4$ solution having the boiling temperature of 107 °C and the highest erosion is caused by $Mg(NO_3)_2$ solution with the boiling temperature of 205 °C. It is worth to note that the boiling temperatures ratio is 1 : 2 and the erosions ratio is 1 : 90.

Table 2: IPT result of silicone rubber using different electrolyte solutions [24], courtesy of Xidong Liang

Electrolyte	ΔW / t g / h	I mA_{Peak}	E_t kJ/min	K	T_b °C
NH_4Cl	0,019	64	3,8	0,45	115
$MgSO_4$	0,007	56	4,6	0,70	107
NaCl	0,021	76	4,8	0,54	109
K_2SO_4	0,017	77	4,4	0,47	103
$(NH_4)_2SO_4$	0,053	79	5,1	0,58	110
$NaNO_3$	0,066	80	3,2	0,30	120
$Ca(NO_3)_2$	0,110	78	4,0	0,40	152
$MgCl_2$	0,350	67	4,9	0,63	195
$Mg(NO_3)_2$	0,630	78	6,0	0,76	205

ΔM/t - the average weight loss per hours of 5 specimens, I - the average measured current, E_t - the average energy dissipated on sample surface per minute K - the time ratio of arc burning time to extinguish time, T_b - the boiling temperature of saturated contaminated solution.

There are also proposal with different wetting manner, with droplets falling on the sample surface [25] or by salt fog [26, 27]. The typical chambers and nozzles can be used for salt fog production according to IEC 601109. The test under rain precipitation of different pH and conductivity was carried out [28].

Gorur proposed a joining of inclined plane test with the dust-fog test [12]. The samples were contaminated by kaolin suspension with addition of NaCl, similar like in solid layer method used for measuring of pollution flashover voltage of insulators. The samples were wetted similar to the IPT but with lower conductivity of electrolyte (100 or 250 µS/cm).

5. VARIABILITY IN IPT RESULTS

The repeatability of IPT carried out according to procedure 1 can be measured as the standard deviation of weight loss or time to damage. Generally, this standard deviation is in the range of 20% and is found as satisfactory. Much greater deviations were noted in dust-fog method. However, two main aspects of the standard procedure generate excessive variability in the test results and in some cases, gross error. This chapter addresses the various sources of variability in the existing test procedure and presents some improvements to reduce the possibility of erroneous test results.

Some papers take the air circulation during the prolonged test into consideration [29]. This factor was not determined by the standard. Noxious gases are generated during the test, so that gas extraction is necessary to protect the operating staff. To strong air circulation accelerates the drying of contamination layer. Without the air circulation the condensation often occur on the sample or on the adjacent parts. The contaminant flow can be diverted, so the time to failure is increased [30]. There are also additional factors which can affect the results of IPT, e.g. UV radiation, compressive or tensile stress [29]. The test conditions as the ambient temperature, humidity and air circulation should be determined in the future standard modification.

A weak voltage source can strongly influence the test results. The standard requires an output voltage stabilized to ± 5% with the rated current not less than 0,1 A for each specimen. It means probably that the maximum voltage drop during the test should be less than 5%. For the highest voltage 6 kV, the rated power should be higher than 0,6 kVA for each specimen. Tests are often simultaneously carried out for a few samples, e.g. for five pieces. In this case the minimum power should be greater than 3 kVA. Some papers give the transformer power of 1 kVA [31] or 5 kVA [32]. It should be stressed that the power requirements are specified for the whole voltage source including autotransformer and high voltage transformer. The autotransformer rated power should be at least the same as that of high voltage transformer.

Sinusoidal voltage shape of a weak source becomes distorted after the arc ignition on the samples. Some

ISBN 978-0-620-44584-9

researches propose to switch-on a shunt capacitance (discussion to the [30]). The capacitance smoothes the voltage wave and reduces the spikes related to arc extinctions. This contributes significantly to the arc re-striking suppression and can significantly extended the live of the test piece. Switching of an additional resistance to the circuit limits the current and the voltage drop. In the case of a very weak source the additional resistance can even reduce the sample life [33]. The opposite effect is expected with a rigid source.

6. TESTS WITH A WEAK VOLTAGE SOURCE

The inclined plane tests were carried out according to IEC 60587 using a typical set up called a "tracker" or an "ageing unit" (Figure 3). A procedure based on method 1: constant tracking voltage applied for 6 hours was adopted. The tracker is built as a panel in which up to five samples can simultaneously be tested. The peristaltic pumps precisely deliver the liquid electrolyte to each of the samples.

The applied voltage was measured using a mixed resistive capacitive (RC) voltage divider. The leakage current was monitored throughout the tests using a 33 Ω resistor. The leakage current and voltage waveforms were acquired using a data acquisition card. The leakage current and voltage signals were acquired at a sample rate of 10,000 samples per second, giving 200 samples for one cycle at 50 Hz. For each cycle of stored leakage current data, the following quantities characterising the leakage current were calculated within the developed LabView routine: r.m.s. and peak values of current, charge, power factor angle, average power, total harmonic distortion (THD) and accumulated energy.

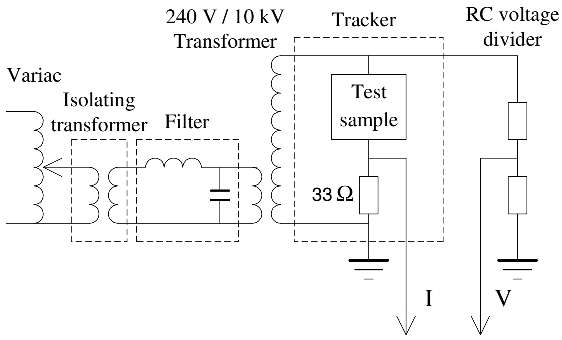

Figure: 3. Test arrangement

A 50 Hz test voltage was applied to the insulator samples using a variable transformer (0 – 275 V, nominal power 2 kVA), an isolating transformer, a low-pass filter and a high voltage transformer (10 kV, 20 kVA). The applied voltage was variable up to 10 kV.

Tests were performed with samples made of RTV-2 silicone rubber with a low amount of filler. The ratio of material weight loss due to erosion to the electrical charge is an important parameter of stress severity. Its value of 0,9 mg/C estimated after the test is twice higher than the value measured by D.C. Jolly for silicone samples exposed to salt fog test [34]. It should be stressed that the value 0,9 mg/C was estimated in test during which only one sample was used.

During the test in which two samples were stressed simultaneously, a significant voltage decrease was observed. At the constant load and the current of 60 mA_{peak} the voltage drop amounted 20%. It is four times more than the value recommended by IEC 60587:1984. As a result of this weak voltage source, the weight loss of one sample estimated after 6 hour of test depends on the number of samples stressed in the tracker (Figure 4). During five samples testing, one hour after the test beginning the voltage dropped from 3,5 kV to 2,0 kV. At this lower voltage the arcs on all samples extinguished. This state lasted for next several ten minutes. Therefore the continuation of the test was useless. The weight loss of a single sample as a function of tested samples can be used to control the rigidity of voltage source. For a powerful voltage source the weight loss of a single sample does not depend on the number of samples tested in the tracker.

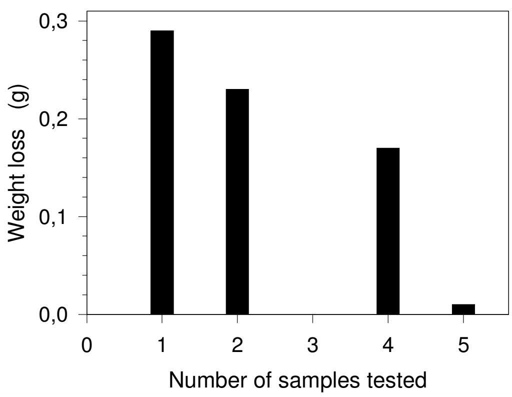

Figure 4: Weight loss of single samples depending on the number of samples tested in the tracker as a result of a weak voltage source.

The high voltage transformer has sufficient power of 20 kVA. However, 2 kVA power of regulating transformer is too low. It should be emphasized that, power of 2 kVA is reached at the full voltage of 275 V. At the test voltage of 3,5 kV, the voltage of regulating transformer is about 1/3 of 275 V. Therefore its power is also only 1/3 of 2 kVA. Taking into account the power losses in a high voltage transformer, a filter and an isolating transformer, this test arrangement is suitable for testing only one sample. The regulating transformer is built into the tracker housing. This solution, used also in commercially manufactured trackers, significantly limits dimensions and power level of a regulating transformer. It could cause significant errors especially when a few samples are simultaneously tested in the tracker.

7. CONCLUSIONS

The best repeatability of inclined plane test results is in the range of 20%. However, in some laboratories appreciably worse outcomes are achieved.

One of possible causes are too weak voltage sources, especially when a few samples are simultaneously tested in the tracker.

8. ACKNOWLEDGMENTS

Prof. A. Haddad, Cardiff University is appreciated for delivery of RTV silicone samples.

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